Summary of Working Group 2 on Beam Quality

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The working group on Beam Quality entertained a number of talks on the topic of how to achieve high quality beams in plasma-based accelerators. The primary focus of discussion was on achieving the conditions of the working definition (below) of a "2nd Generation Plasma Accelerator." In addition, the group was charged with answering the following question: What are the limits on the maximum charge that can be accelerated in a Self-Modulated Laser Wakefield Accelerator? The results of these discussions are briefly summarized here.

The working definition of a 2nd Generation Plasma Accelerator is taken to be one with the following beam quality (see proceedings of past workshops in this series – IEEE Transactions on Plasma Science Special Issue, April 2000)

Normalized Emittance: 10π mm-mrad

Fractional Energy Spread: 5% Number: 10⁸

Transverse beam quality has been demonstrated in the well collimated beams from a number of recent laser experiments in the self-modulated wakefield regime as well as in the recent beam-driven wakefield experiment E-157 at SLAC (emittance preservation demonstrated over a meter of plasma). It has been shown at past meetings that longitudinal beam quality boils down to appropriate strategies for injecting the beam load in the proper phase of the plasma wave. Specifically, a number of strategies were discussed as summarized in Table 1. The first item in the table is not an injector scheme, but rather a strategy for obtaining proton beams by laser acceleration in solid targets. The remaining items in the table pertain to electron beams accelerated in gas/plasma targets.

In general it was concluded from the discussion that any or all of the injection strategies in Table 1 are capable of yielding the kind of beam quality referred to above. The various ideas are at varying stages of development; however, it is likely that one or more

will be in operation by the time of the next meeting of this workshop in two years in Italy.

One interesting theme of the working group this time was the recognition that the condition that the bunch length be very short to avoid energy spread could be significantly relaxed. Conventional wisdom (and test particle simulations) had held that achieving 5% energy spread on a light beam load injected at the phase velocity of the plasma wave required that the injection phase or bunch length subtend less than 20 degrees or a one-twentieth of a plasma wavelength. Longer bunches sample different field strengths and hence develop energy spread. At the 300 micron and shorter wavelengths typical of plasma accelerating structures, this requires injection of 50fs or shorter pulses. However, as was pointed out in the talk by Reitsma, the use of substantial beam loads flattens the wake in the vicinity of the beam and relaxes this condition. Furthermore, the use of lower energy injected beams allows self-consistent bunching of the beam during the backward phase slip of the bunch, as was pointed out by Andreev and in the paper by M. Ferrario et al. in the IEEE Proceedings above. In each case, the requirement on bunch length is relaxed and the technical barrier to achieving 2nd Generation beam quality in the near term is considerably lowered.

The Working Group Questions:

What are the limits on the maximum charge that can be accelerated in a Self-Modulated Laser Wakefield Accelerator? What is the respective importance of each of the following: a) beam loading, b) space charge and c) the Alfven limit?

The Answers:

a) Beam Loading: The beam loading limit for a particle bunch in a plasma wave is normally found by setting the wakefield of the bunch equal to the laser wakefield amplitude (T. Katsouleas, Part. Accel 1987). This corresponds to total absorption of the wave energy. We multiply this by a factor R of order 10 because of the observation is simulations that the relatively long laser in the SMLWFA case can repeatedly re-excite the wave after it is beam loaded. The maximum beam load is then

$$N \approx 5x10^5 \sqrt{n_o} \frac{n_1}{n_o} AR$$

Where, n_1/n_0 is the fractional wave amplitude (typically .5 from simulations), A is the effective cross-sectional area of the wave (typically 300 μ^2), n_0 is the plasma density (typically 10^{19} cm⁻³). Substituting typical values yields an estimate of

$$N \sim 10^{10}$$
- $10^{11} \sim 1$ - 10 nCoul

This is not far from the number observed in recent experiments, suggesting that these are nearly optimized from the point of view of charge production.

b) Space charge: The relative importance of space charge in relativistic beam propagation is given by the space charge parameter ρ :

$$\rho = \frac{2I}{I_A} \left(\frac{\gamma^2 r^2}{\varepsilon_N^2} \right)$$

Where I_A is the Alfven current = 17 $\beta\gamma$ kA, ϵ_N is the normalized emittance and r is the spot size of the beam. This parameter reflects the ratio of the space charge and emittance terms in the equation describing the evolution of the envelope of a beam as it propagates in free space. For typical parameters, this number is much less than one in the plasma of a SMLWFA. Moreover, the plasma adds focusing terms which dominate over and further reduce the effect of space charge. Thus we conclude that in the plasma the beam is emittance dominated, and despite the large currents, space charge is not a limiting factor. The situation changes dramatically once the beam exits the plasma. Within a few millimeters the beam expands (due to its emttance) enough that ρ becomes larger than one and the beam propagation is then in the space charge dominated regime.

c) Alfven Current: The Alfven current is roughly the current at which a beam's self-magnetic field becomes large enough that in the absence of other forces a particle on the edge of the beam would be turned around within the beam radius. As described above I_A is $17kA *\beta \gamma$ while the peak currents of the micro-bunches may be of order 1 nCoul in $\lambda_p/10\sim 6$ fs or 170 kA. In the plasma, the strong focusing of the plasma wave can overcome the Alfven limit. Once the beam exits the plasma, we may expect that the Alfven limit may be exceeded for the lower energy particles. We might expect some of these to be turned around or lost from the beam.

In summary, the limiting mechanism on beam charge in SMLFAs is beam loading, and current experiments seem to be operating near this limit. However, the space charge and Alfven limits may be important once the beam leaves the plasma. The dynamic evolution of dense beams exiting a plasma accelerator have received relatively little attention and raise interesting and important questions for future research.

Table 1. Injection Strategies

Concept	Theory/Sim Status	Experimental Status
Snowplow accel. Of protons	Sim's show GeV beam	Prospects for 300-
in solid targets (moving	Theory explanation needed	600TW/30-60fs
double layer)		experiments at LOA, RAL, UM
Classical Photocathode	Yes	Plans at Eindhoven
		(2.5+MeV, 100fs), UCLA
		(16 MeV w/ mag.
		Compression), Orsay (but
		ps not fs)
Adiabatic Buncher	Modeled except for self-	
	wakes in plasma	
LILAC/Colliding Pulses	Yes	Prelim from UM; UCLA prelim null result
Plasma Klystron (short	Yes	Possible at UCLA
plasma buncher plus drift space)		
SMLWFA as first stage	- ·	Plans at LOA, RAL, LBNL
(Plasma Gun)		
IFEL Buncher	Yes, for test particles	Possible at UCLA, LBNL; POP expt at 10µ at BNL